Simulation of Fuel-Coolant Interaction in Stratified Configuration in Reactor Geometry

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ABSTRACT

During a hypothetical severe accident in a light water nuclear power plant, the molten reactor core may come in contact with the coolant water. One of the consequences can be a vapour explosion. In nuclear safety, the vapour explosions are typically analysed in the melt jet-coolant pool geometry. In the stratified melt-coolant configuration, which was less analysed, a layer of melt spreads below a layer of coolant. The stratified melt-coolant configuration was believed to be incapable of producing a strong energetic interaction between the melt and coolant. This belief was based on the conclusions from the past theoretical and some experimental research with simulant materials, where interfacial instabilities of the melt were not observed and consequently the interface was almost flat, yielding a strong hypothesis of the subsequent models.

However, the results from recent experiments performed at the PULiMS and SES facilities (KTH, Sweden) with corium simulant materials contradict this hypothesis. In some of the tests, a premixed layer of ejected melt drops in water was clearly visible and was followed by strong spontaneous vapour explosions. Based on the past experimental and analytical research, model for the melt-coolant premixed layer formation in stratified configuration was previously developed.

With our model, pioneering analysis of premixed layer formation and vapour explosions in stratified configuration in reactor geometry was performed and is presented in the paper. The purpose of our research is to improve the knowledge, understanding and modelling of the fuel-coolant interaction and vapour explosion in stratified configuration in reactor-like conditions. Performed simulations with the MC3D code (IRSN, France) are demonstrating the model's capability to describe the premixed layer formation in the reactor geometry. Further, the simulations of vapour explosion are performed to assess the possible pressure loads on the reactor cavity during vapour explosions, which is of high interest in nuclear safety.

1 INTRODUCTION

During a hypothetical severe accident in a light water nuclear power plant, the molten reactor core may come in contact with the coolant water. The interaction between them is known as a fuel-coolant interaction (FCI). One of the consequences can be a rapid transfer of a significant part of the molten corium thermal energy to the coolant in a time scale smaller than the characteristic time of the pressure relief of the created and expanding vapour [1]. Such a phenomenon is known as a vapour explosion. Given possibly large amount of thermal energy, initially stored in the liquid corium melt at about 3000 K, and pressure peaks of the order of 100 MPa, vapour explosion can be a credible threat to the structures, systems and components inside the reactor containment. It can also threaten the integrity of the reactor containment itself, which would lead to release of radioactive material into the environment and threaten the general public safety.

Typically in nuclear safety, the vapour explosions are mostly analysed in the melt jet-coolant pool configuration. Some experimental work has been done in the past related to the stratified configuration (Figure 1). In most cases, non-prototypical materials with melting temperatures lower than that of the reactor fuel, were used. Based on the conclusions from the past experimental and analytical research, the stratified melt-coolant configuration was believed to be incapable of producing a strong energetic interaction between the fuel and coolant [2]. However, the recently performed experiments in the SES and PULiMS facilities at KTH (Sweden) with a superheated high melting temperature eutectic corium simulant melt resulted in relatively strong spontaneous vapour explosions and consequently raised the interest in stratified vapour explosions again. The clearly observed premixed layer in the PULiMS and SES experiments with splashes of melt [3] was in contradiction with the previous assumption about the absence of the premixing phase in the stratified melt-coolant configuration. Based on the comprehensive overview of the recent and past experiments and modelling research, model for the premixed layer formation in stratified configuration was developed [4].

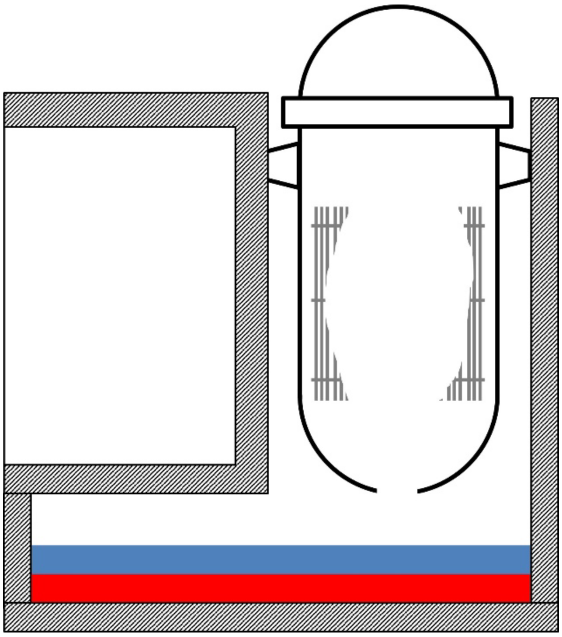

Figure 1: Stratified melt-coolant configuration - a layer of melt lies below a layer of coolant. At reactor conditions, the melt can potentially spread on the large area of the cavity floor.

Application of the model was already validated on PULiMS E6 and SES S1 tests with relatively good agreement with the experimental results [4]. Simulation results have shown that the strength of the steam explosion could be primarily attributed to the premixed layer formation. In our current research, the model for the premixed layer formation was applied to the reactor geometry.

2 SIMULATION APPROACH

The developed model for premixed layer formation was implemented as a patch in the computational fluid dynamic MC3D code V3.9.0.p1, which is being developed at IRSN (France) with fuel-coolant interactions in mind. MC3D is one of the leading codes in the field of fuel-coolant interactions and it is suitable for the planned purpose, because it covers both the premixing phase and the explosion phase of the fuel-coolant interaction. The premixing phase module [5] deals with the initial mixing of the melt and the coolant and this module was upgraded with the premixed layer formation model, developed in the frame of our research work. In case that a vapour explosion occurs, the results from the premixing phase module serve as an input for the explosion phase module. The explosion phase module concerns the fine fragmentation of the melt during the explosion and the heat transfer between the created fine fragments and the coolant.

The complex phenomena of premixed layer formation as described by our model was simulated for a generic PWR-like geometry (Figure 2), similar to the one used in the OECD/NEA SERENA project [6]. The reactor cavity has a diameter of 4.9 m and height of 10 m. At the side, a shaft was added at the height of 1 m. The 3D calculation domain (22×10×26 cells) contains half of the reactor cavity, applying symmetry boundary conditions at the symmetry plane.

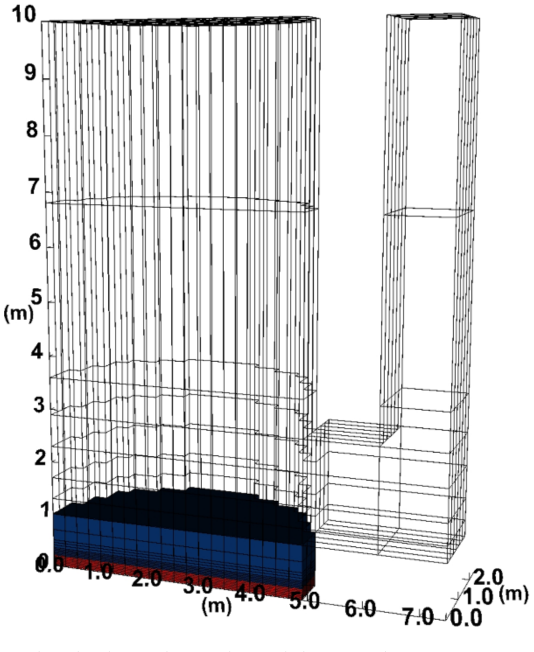

Figure 2: Calculation domain with xz-planar symmetry.

The simulation case has a 20 cm high melt pool at the bottom. The initial melt temperature was 3228 K, which corresponds to 323 K of superheating. Material properties were the same as in the SERENA project. Water at temperature of 323 K was added on top up to height of 1 m.

Simulations were divided into the premixing phase and the explosion phase. In the premixing phase, mixing of melt and water according to our model was simulated. Results from the premixing phase, calculated with our model, served then as an input for the simulation of explosion phase. The explosion was triggered at the centre of the premixed layer.

3 RESULTS

Firstly, the premixed layer formation phase was simulated. After the initial transient of first melt drops being ejected, quasi-stationary conditions are developed. The melt drops are constantly being ejected from the continuous melt and coalescing back. In Figure 3, the formed premixed layer after 2 seconds is shown. At the bottom, there is a pool of melt with the ejected melt drops above it. The melt drop volume fraction increases towards the top of the premixed layer because the velocity of the melt drops decreases. The phenomenon of the premixed layer formation is not completely homogeneous, which indicates the complexity of the feedback loops. Namely, heating of the coolant water, vaporization and flow currents of the vapour, water and melt affect the height of the premixed layer and the melt fraction distribution.

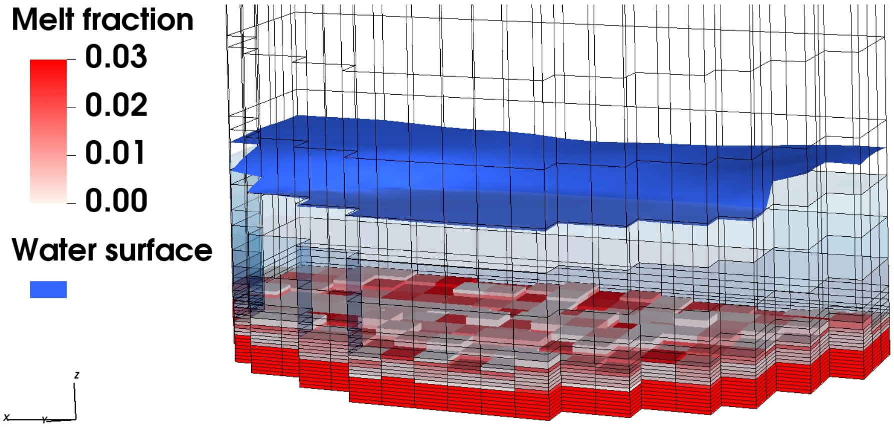

Figure 3: Premixed layer for the base case. Melt volume fraction is shown, where it is larger than 10^{-4}. For illustration, contour of water surface is presented.

Further assessment of our model for the reactor conditions is made for the explosion phase (Figure 4). In the analysis, simulated force signals on the bottom of the domain and total gained impulses are compared (Figure 5).

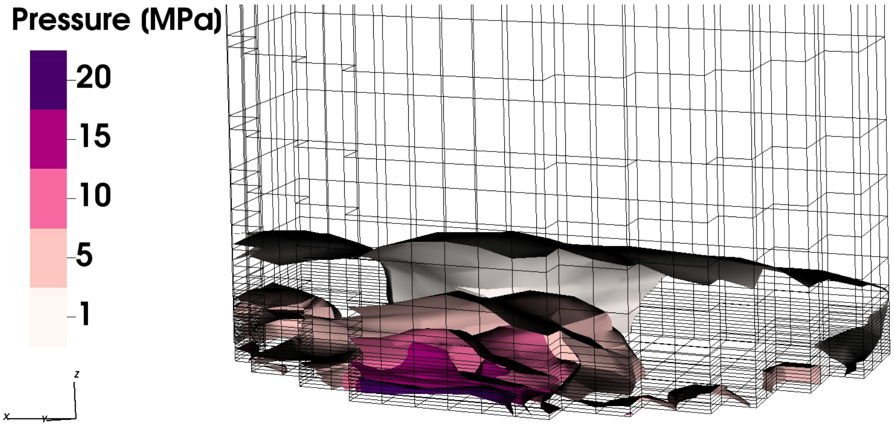

Figure 4: Pressure contours during the explosion simulation for the base case. Locally, pressure is above 60 MPa.

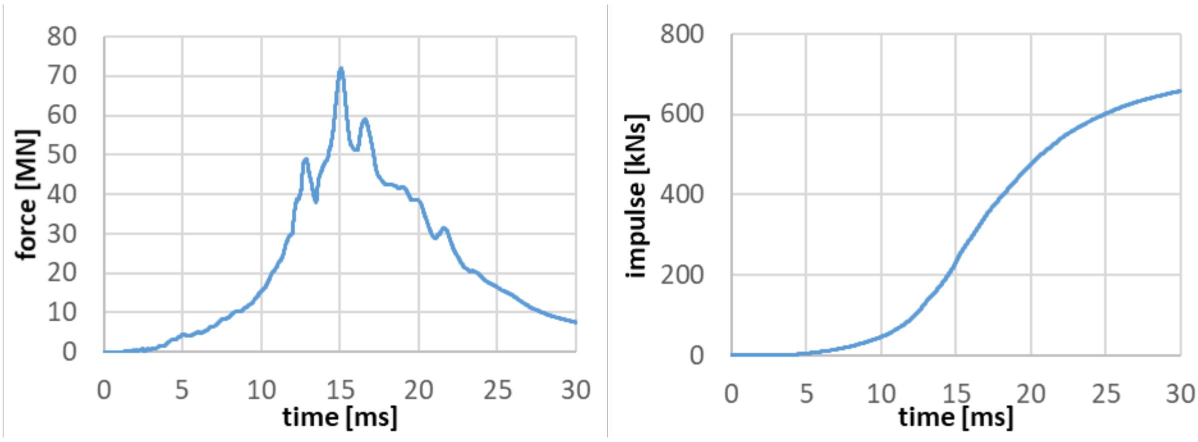

Figure 5: On the left: Force on the bottom of the reactor cavity. On the right: Total force impulse on the reactor cavity bottom.

It can be seen for the simulation case that about 10 ms is needed for the explosion development. The force on the bottom plate reaches maximum of about 70 MN at around 15 ms, slowly decreasing afterwards. The duration of the explosion, calculated as the total force impulse divided by half of the maximal force, is around 20 ms, which is significantly longer compared to the medium-scale experiments (PULiMs and SES) and can be explained by the dimension difference of the premixed layer in both cases. The total gained force impulse is, for the reactor geometry, more than two orders of magnitude larger compared to the mentioned experiments, but again in agreement with the dimension difference.

Other parameters, critical for the analysis of loads on the reactor cavity structures, are maximal pressure and pressure impulse. The maximal pressure during the explosion of more than 60 MPa is achieved in the bottommost cell near the side wall. The pressure impulse is calculated in few cells across the domain. The largest pressure impulse is achieved at about half the height of the melt pool and it is over 50 kPa·s. Both values are comparable to the analysis of the vapour explosion in the melt jet-coolant pool geometry, assessed as a part of the SERENA project [7].

4 CONCLUSIONS

With our model, pioneering analysis of premixed layer formation and vapour explosions in stratified configuration in reactor geometry was performed.

A large risk of potential strong vapour explosions in stratified configuration can be indicated from the analysis results with pressure peaks of more than 60 MPa and local pressure impulses of over 50 kPa·s, comparable to the analysis of the vapour explosion in the melt jet-coolant pool geometry. Over hundred times larger force and force impulse on bottom was observed compared to medium scale PULiMS and SES experiments.

This preliminary analysis of the vapour explosions in stratified configuration in reactor geometry indicates the importance of the in-depth analysis of such phenomena for the nuclear safety. For more reliable assessment, further detailed analysis is advised.

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